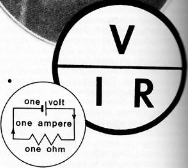
OHM . . .

the unit of electrical resistance is named for the German professor GEORG SIMON OHM whose investigations resulted in the famous law that bears his name . . . . .



OHM'S LAW ($I = V/R$) - The current in an electrical circuit is directly proportional to the voltage in the circuit, and inversely proportional to the resistance in the circuit. The law applies to linear, constant-current circuits.

The circle above symbolizes the Ohm's law relationships. When a finger tip covers the factor that is wanted, the other two factors of the Ohm's law equation are shown in the relation for the required calculation.

OF ALL LAWS relating to the applications of electricity, one of the most pervasive and practical is that symbolized in the circle at the right. Called *Ohm's Law,* it immortalizes the name of its discoverer, the 19th century German professor, Georg Simon Ohm.

Working against the odds of poverty, isolation and obscurity, he laid the foundations that established the relations between the potential, the flow of current and the resistance in an electric circuit. Unrecognized, and derided by some at first, the soundness and basic importance of his findings at last achieved an international acclaim, giving him an eternal niche in the gallery of founders of the electrical science.

To review the conditions that led up to Ohm's crucial law, the following paragraphs present briefly the state of electrical knowledge in the early nineteenth century.

Up to about the year 1800, the electricity that was experimented with, and had been known from antiquity, was the electricity from friction. This involved the electrical charges produced by rubbing

on a suitable material such as glass or hard rubber. Electrification was a popular science, and also a pseudo-science for medical quackery. The early workers made large, powerful electrical machines, and experimented with sparks, shocks and the strange purple glow given off by the high intensity electrostatic discharges in evacuated vessels.

Eighteenth century investigations with frictional electricity exhibited the differences between electrical conductors and non-conductors, and showed that charges could flow long distances in wires, leading some to believe that electricity was a fluid. It was also evident that charges, though separated, could affect each other across the intervening space by an inductive action. Experimenters showed heating and chemical effects from electricity, and there were glimmerings of a reciprocal relationship between electricity and magnetism.

Charles A. Coulomb, showed, in Paris, in 1785, that electrical charges attracted or repelled each other in proportion to their magnitude, and that the force between point charges varied inversely with the square of their separation. With this quantification of charge by Coulomb the science of electrification had reached a plateau. The 18th century closed with the work of Luigi Galvani, in Italy, whose investigations with animal tissue had developed a new effect which he called "animal electricity."

FROM ITALY, in 1800, came an announcement of a revolutionary new kind of electricity. Alessandro Volta, inventing new principles from the pioneering work of Galvani, revealed that he had produced, for the first time, a "continuous and inexhaustible source of electricity." He used alternate interconnected disks of zinc and copper, separated by pasteboard soaked in brine, to create the "electric pile." In contrast to the spasmodic spark-type discharges from the frictional electrical machines, the scientific world now was provided with a new and ready means to produce sustained and large electrical currents conveniently and at a controllable potential.

The value of Volta's contribution was immediately recognized, and the availability of electric power from batteries soon opened new fields of discovery. Shortly after Volta's invention it was found, in England, that the wires from a battery, dipped into acidified water, decomposed the water into its elements hydrogen and oxygen. Then, in 1807, the separation of the new elements, sodium and potassium, from their salts was achieved with an electric current by Sir Humphry Davy, in England.

In the twenty years following Volta's great discovery, experimentation with the chemical and heating effects of electric current were vigorously pursued. But one important effect, the interrelationship of electricity and magnetism, escaped clear observation until 1820. In that year a new era of electricity began with the startling announcement to the scientific world by Hans Christian Oersted at the University of Copenhagen, that a wire carrying an electric current is accompanied by a magnetic field of force. He found that the magnetism surrounded the wire, and circulated at right angles to the direction of the flow of current.

Oersted's discovery sparked a flood of new investigations. Now, in addition to the electrical effects, the new phenomenon of electromagnetic action was opened, so that the dynamic forces of magnetism could be studied and used.

WITHIN A FEW MONTHS after the Oersted announcement, André Marie Ampère, in Paris, demonstrated that parallel conductors carrying current would exert magnetic forces on each other. There was a mutual attraction or repulsion, which depended on the direction of the current. He showed that the force was proportional directly to the intensity of the current, and inversely proportional to the separation of the conductors.

Then Ampère revealed that wire wound into a coil, which he called a "solenoid," acted like a bar magnet, having definite north and south poles. The solenoid arrangement, would in the future, become basic to operation of electromagnetic apparatus..

Ampère further conceived that a tension, which he called "electric potential," existed between the terminals of a battery, and that the "intensity" of the current provided the energy of the output.

In the early nineteenth century, the concepts of electric potential and intensity were largely descriptive. The quantitative relationships had not yet been formulated. There was no clear distinction between the electromotive force of a battery, and the resulting flow of current, although it was apparent that they were being consumed in the circuit to produce heat or mechanical or chemical effects. Very importantly, Ampère had noted a

property of a conductor which he called *resistance.* This appeared as an impediment to the flow of the current. He saw this as an "imperfection" in a conductor. The resistance due to the imperfections in a conductor was a factor limiting the current in the conductor.

Some studies of electrical resistance as related to size and shape of conductors had been made. But the significance of resistance as related to the electromotive force and the current in the circuit had not been defined. Progress of electrical investigation was being retarded by lack of exact analysis and formulation of these fundamentally related factors. Bringing order to this situation, and putting circuit measurement on a precise foundation, was to be the epochal work of Ohm.

GEORG SIMON OHM (christened as Johann Simon) was born 16 March 1789 at Erlangen, Bavaria, then a principality in southern Germany bordering on Austria. He was the older of two sons of Johann Wolfgang Ohm, a master locksmith, a man of ability, and with interests in philosophy and science. Although the family was not well-to-do, the father had ambitions for the scholarly advancement of his sons. He, in his youth, had been instructed in mathematics, in return for rent, by a student lodged in the parental home, and this gave him a strong feeling for the value of a formal education. It also enabled him to teach his sons the rudiments of mathematics and some physics and chemistry.

George, and his brother Martin, were also indoctrinated into the writings of Kant and Fichte, contemporary German philosophers who were wrestling with the morality problems in an era of advancing science. Kant believed that man's inherent rationality would prevent a social-moral conflict: that along with his power to develop pure and applied science, man had the inborn ability to guide his conduct in the growing age of reason.

While it was the father's thought that the two sons would eventually join him in the locksmith business, he was ambitious for their further formal education, so they were sent to the local Gymnasium, a preparatory school for a university. Five years there gave them a basic classical training. The brothers displayed ability, Georg leaning to science and his brother Martin toward mathematics. The talents of both brothers were particularly remarked on by Prof. Langsdorff, head of the mathematics department at the Gymnasium, who predicted that history would repeat itself in them the brilliance of the 18th century Bernouilli brothers, who were famous scientists and mathematicians.

In view of their outstanding abilities the brothers were enrolled at the University of Erlangen. Georg's first stay there was short. A family disagreement over his school social conduct led to a kind of exile in Switzerland. He supported himself there by tutoring and was able to save enough to continue his education.

In 1811 Ohm returned to the University of Erlangen where he received a Doctor of Philosophy degree and a modest position teaching mathematics. However, the low salary and poor prospects for advancement led Ohm to seek employment elsewhere. Anxious to repay his father for the sacrifices he had made, he petitioned the King of of Bavaria for a new appointment. This was granted, but the best he could obtain was a disappointing and poorly paid post in a secondary school at Bamberg. Even this position came to an end in 1816 with the closing of the school as an aftermath of the general unsettlement that followed the overrunning and disruption of Germany in the Napoleonic wars.

While at Bamberg Ohm had written an *Essay on Geometry,* which embodied his ideas on the usefulness of a mathematical education, and the self-reliant attitude a student should have in the pursuit of knowledge. Ohm sent published copies of his work to the reigning monarchs of Germany with a plea for help in securing a more suitable employment. The Prussian King, Friedrich Wilhelm, looked favorably on Ohm's request and he was appointed a principal teacher in mathematics and science at the reformed Jesuit Gymnasium of Cologne. There Ohm found a friendly accomodation to his abilities and interests. He remained at Cologne for nine and a half years.

THE SCHOOL AT COLOGNE had well-equipped laboratories, and his involvement in teaching science stimulated in Ohm a new and ardent interest in physics. To get into the mainstream of the current science he immersed himself in the classic books of the time in science, particularly the works of the French mathematicians and physicists: Lagrange, Laplace, Legendre, Biot, Fourier, Poisson and Fresnel. The discovery of

electromagnetism by Oersted, and the work of Ampère, Biot and Davy particularly captivated Ohm's imagination. He began a program of experiments in electricity and magnetism, leading to his study of the galvanic circuit that was to be a major part of his life's work.

OHM was a successful teacher. But his ambition was for a university post that would give him more time for physical research. As the years at Cologne moved on, Ohm saw that he was reaching a dead end. His teaching duties were heavy, and although his consciencious work was appreciated, there was little possibility of promotion that would allow more time for personal pursuits. The same disappointments of earlier teaching positions were being repeated. His only hope was to seek an environment of greater promise. Desperateness of his situation now prompted the same solution that had worked before to get a favorable notice. He must publish, and this must be based on some worthy research.

Although burdened with teaching, and with slender resources, Ohm threw himself into a series of experimental efforts on the question of electrical relationships that were pressing for a resolution. His accomplishments were slow. But persistence and a perceptive mind, plus the mechanical skills acquired in his days as a locksmith, produced over a period of several years, the experimental results and mathematical formulations that were finally to make him famous.

What were the conducting powers of wires and other conductors? What was the effect of different metals, and the various lengths and cross-sections of wires in the electrical circuit? How did they relate to the output of a battery as the current coursed through the conductors of the circuit? These were questions that had occupied investigators before and during the time Ohm began his researches.

THE FIRST EXPERIMENTS in conductivity were those of Henry Cavendish (1731-1810), a reclusive English investigator whose notes were unknown until published by J. Clerk Maxwell in 1879. Cavendish's work was done before the availability of voltaic current. Using the discharges of Leyden Jars for power, he tested the relation of potential drop to current flow through glass tubes of various lengths and diameters containing a salt solution. Lacking instruments, Cavendish measured the "degree of electrification" by the amount of shock he received in grasping the terminals with his hands to complete the circuit through his body. Maxwell commented that Cavendish's results were remarkably accurate.

Cavendish expressed the outcome of his tests with a statement that the "resistance is directly as the velocity." He meant by "resistance" the whole force which resists the current, and by "velocity" the strength of the current through unit of area of the section of the conductor. In the estimation of Maxwell, Cavendish's results were an anticipation of the law of electrical resistance discovered by Ohm, but obviously Ohm knew nothing of the work of Cavendish.

Sir Humphry Davy (1778-1829) and Peter Barlow (1776-1862) in England, and A. Becquerel (1788-1878) in France, experimented with wires of various metals, using voltaic cells for their source of electricity. They were primarily interested in the conducting power of different wires. This experimenting was being done at a time when the quantitative circumstances of the electric current was being designated by such terms as "intensity of electricity," "excitation force," "quantity of electricity," and "tension," to which terms no accurately defined meaning was attached.

THE DISTINCTION between electrostatics and and the electric current was not always clear. The concepts of electrostatics, the older science, left it uncertain whether flow of electricity was a surface phenomenon, as with electrostatics, or a function of the interior structure. The term "resistance" was used for different quantities, and did not have its modern meaning. Instruments were primitive, yielding only rough results. The gold-leaf electroscope was used to measure electric charge; the magnetic torsion balance and other early forms of galvanometers were used for measuring current. The early voltaic cells were subject to polarization and gave an unpredictable output. The cell's inner resistance was a factor not well understood.

Davy found that the load imposed by wires of a given material having the same ratio of length to section was the same. Barlow also sought a relationship between current intensity and the length

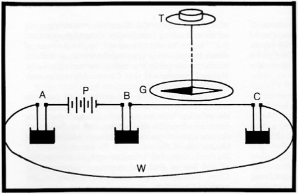


Fig. 7.1- OHM'S APPARATUS for testing conductivity relationships between metal wires of various dimensions. Terminals of the voltaic pile, P, dip into mercury cups, A and B. An "invariable" conductor ran between B and C, under the needle of a Coulomb-type torsion balance, G, to measure the electromagnetic force when the "variable" test wires connected between A and C, completed the circuit.

and diameter of a wire. He concluded that the current intensity was approximately proportional to the square root of the length, and for wires of the same length the current intensity increased with the diameter of the wire.

Becquerel approached the problem from the point of view of the electrical flow in the circuit. He considered the potential, or tension, of the voltaic cell to result from two fluids, originating equally from the two poles of the cell, and diminishing toward some central point in the circuit. He pictured the diminution of tension as an arithmetrical decline from both poles, which would indicate that something to do with the current would remain constant in the circuit. Becquerel showed that the conductivity of wires of the same metal, having the same ratio of length to cross-section, was the same. This was equivalent to finding that the conductivity of the metal, per unit volume, remained constant, and was independent of the current.

Ampère had first drawn the distinction between electric tension and the intensity of the current. This opened the possibility that one of these elements might be the constant factor and the other a varying factor in the resolution of the flow around the circuit.

Ohm was familiar with the reports of these contemporary investigators. He noted the differences in their results, and set out to reconcile them with experiments of his own. He took up his researches in the effort to sift out the true situation.

OHM'S FIRST SCIENTIFIC PAPER, published in 1825, dealt with the relationship between the length of a wire carrying a current, and the loss of magnetic force due to that length. The apparatus, Fig. 7.1, used voltaic cells for the electric source. The upper circuit, A,B,C, including the cells, P, and the wire from B to C for energizing the compass needle, G, Ohm called the "invariable conductor."

Using this fixed source, he then added to the circuit the test wires, W, which were the "variable conductors." When the circuit was completed, the needle, G, suspended from torsion head, T, over wire, BC, was deflected. The deflected needle was then returned to zero by twisting the torsion head. The torsion reading was a measure of the force of the current.

For the series of tests, Ohm used a short, thick wire to give a "normal" or reference reading. Compared to this were the lesser readings of six thinner wires ranging in length from one to seventy five feet. Ths loss in force was expressed as the difference between the normal force of the reference wire, and the smaller force exerted by the test wires, divided by the normal force. The loss in force was actually proportional to the change in current corresponding to the length of the test wire. It was an indication of a variable in the circuit related to the dimensions of the test wires.

Ohm found that a relationship between the force and the length of the test wires could be expressed empirically by the equation:

$$v = m \log\left(1 + \frac{x}{a}\right)$$

where, v, is the decrease in force, x, the length of the conductor, and, a, the length of the reference wire. For the coefficient, m, Ohm reported: "The coefficient, m, is a function of the standard force, of the thickness of the conductor, of the quantity, a, and, as I have reason to believe, of the electric tension of the force. I am at the moment, still engaged in making quite sure, through more exact experiments, of the exact nature of the function."

CONDUCTION of wires differed not only with dimensions, but also with the metal composition. The relative conductivity of various metals had been investigated by Davy, Barlow and Becquerel, but their results differed markedly.

Ohm proceeded with a series of new tests to determine the conductivity of a variety of metals. His investigations involved three factors: 1- the length of the conductor, 2- the conductor section, and 3- the conductor material. Using the same apparatus, Fig. 7.1, as in his previous work, he tested the relative conductivity of nine different metal wires. As a reference metal he used a copper wire of a certain length and section. Its reading he arbitrarily took as 1000. Then, using wires of other metals, he maintained the same section but varied the length to get the same reading as the copper reference. The ratio of length for the various metals thus indicated the proportionality to copper.

One series of comparisons reported by Ohm is

copper	1000	iron	174
gold	574	platinum	171
silver	356	tin	168
zinc	333	lead	97
brass	280		

shown in the table above. Ohm later found an error in the reading for silver, due to faulty measurement of the wire. Silver proved to be a better conductor than copper. Except for this, Ohm, in the table, had determined the correct comparative order of conductivity for the metals. His results were later corroborated by many others.

From his experimental work it was apparent to Ohm that an increase in cross-section, and a reduction in length, increased the conduction. Furthermore, the conductivity was a unique property of each individual metal. Ohm formulated his data into a law to the effect that:

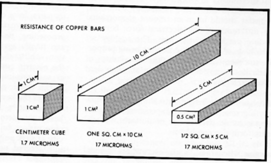
Electrical conductors of the same substance but different diameter, have the same conductivity in their lengths in proportion to their cross-section.

This is expressed for copper in Fig. 7.2.

Ohm's results appeared in two German publications, one edited by J.S.C. Schweigger, and the other by J.C. Poggendorff, both of whom had been active in the development of early galvanometers. The articles did not, however, attract much atten-

OHM'S PROPORTIONAL RULE

Fig. 7.2 - Resistance of a conductor is not altered if the cross-section is kept proportional to the length. Two bars at right have the same resistance. Cube at left is the ohm-centimeter resistance of copper.



tion, and Ohm's work did not impress his contemporaries. Despite this Ohm forged ahead with his experiments to resolve the problem that had confronted and long intrigued him: *the fundamental forces in an electric circuit.* He was seeking a law to define the relationship between the electric force, the resulting electromagnetic intensity, and a length of the connecting wire. What was the nature of the attenuation of the battery's tension as the conductor was lengthened or its section reduced? Did conductibility vary with the strength of the current? At this point Ohm found the beginnings of an answer in the work of a French scientist.

JOSEPH FOURIER (1768-1830), the French mathematician and physicist, published in 1822 a work entitled: *The Analytic Theory of Heat* that attracted the attention of the scientific world. One of its subjects was a discussion of the flow of heat in materials, that is the conduction transfer of heat from a higher temperature extremity to a lower one. Fourier summarized his results in a mathematical law stating that the quantity of heat flowing in time in a given direction is the product of the conducting area normal to the path, the temperature gradient along the path, and a property of the material known as the thermal conductivity. Fourier assumed the conductivity of a material to be constant for all temperatures.

Ohm was struck with the analogy to an electric circuit. He saw similarity in the heat flow in a metal rod to the electrical flow in a conductor. He was the first to grasp the association of the flux of heat to the transfer of electricity from one particle to the next in a wire. And, in analogy with heat, this transfer should be in an amount proportional to the difference of the electrical force between succeeding particles of the wire. The analogy set him thinking of the electric flow as being proportional to the tension, and the possibility of Fourier's heat transfer equation in an equivalent form for electricity.

OHM opened his insight into the galvanic situation by a geometric thought experiment, using the simplest possible circuit, one of uniform material and a uniform size conductor:

"Imagine," he wrote, "a ring everywhere of equal thickness and homogeneous, having at any one place one and the same electric potential, i.e., inequality in the electrical state of two surfaces situated close to each other; from which causes, when they have come into action, and the equilibrium is consequently disturbed, the electricity will in its endeavor to re-establish itself, if its mobility be solely confined to the extent of the ring, flow off on both sides.

"If this tension were merely momentary, the equilibrium would very soon be re-established; but if the tension is permanent, the electricity by virtue of its expansive force, which is not sensibly restrained, produces in an almost inappreciably brief space of time, a state which approximates closely to equilibrium, and consists in this: that by the constant transmission of the electricity, a perceptible change in the electric condition of the parts of the conductor through which the current passes is nowhere produced.

"The peculiarity of this state, which occurs also frequently in the transmission of light and heat, arises from the fact that each particle of the conducting medium situated in the circuit of action receives each moment just the same amount of the transmitted electricity from the one side as it gives off to the other, and therefore constantly retains an unchanged quantity.

"Now, since by reason of the first fundamental position the electrical transition only takes place directly from the one particle to the other, and is under otherwise similar circumstances, determined according to its energy by the electrical difference of the two particles, this state must evidently indicate itself on the ring uniformly excited in its entire thickness, and similarly constituted in all its parts, by a constant change in the electric condition, originating from the point of excitation, proceeding uniformly through the whole ring, and finally again returning to the place of excitation; whilst at this place itself, a sudden spring in the electric condition constituting the tension, is, as was previously stated, constantly preceptible. In this simple separation or division of the electricity lies the key to the most varied phenomena.

"The mode of separation of the electricity has been completely determined by the preceding observation; but the absolute force of the electricity at such point by the length of a perpendicular line erected upon it; that directed upward may represent a positive, but that downwards a negative

OHM'S THOUGHT EXPERIMENTS . . .

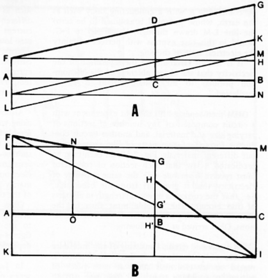


Fig. 7.3 - These graphical representations were part of the reasoning used by Ohm in arriving at the relations in the galvanic circuit. The length of the circuit is shown by the horizontal lines, the tension by the vertical lines, and the fall in tension by the sloped lines. "A" is a circuit of uniform material and uniform size of the conductor, and "B" is a circuit of two differenct metals of the same thickness. Ohm assumed the current to be constant, the tension (potential) falling in proportion to the conducting powers of the circuit.

From *The Galvanic Circuit Investigated Mathematically* by G.S. Ohm, translated by William Francis at the University of Berlin. Van Nostrand Company, New York (1891 edition), the Kraus Reprint Company, New York (1969 reprint).

electrical state of the point.

POTENTIAL or TENSION and its fall may be graphically represented:

"The line A-B, Fig. 7.3A, may accordingly represent the ring extended in a straight line, and the lines A-F and B-G perpendicular to A-B may indicate by their lengths the force of the positive electricities situated at the extremities of A-B.

"If now the straight line F-G be drawn from F to G, also F-H parallel to A-B, the position of F-G will give the mode of separation of the electricity, (or, as we should now express it,'the difference of potential that exists between the extremities or the total electromotive force at work in the circuit.') and quantities B-G, -A-F or G-H the tension occurring at the extremities of the ring; and the force of the electricity at any other place, C, may easily be expressed by the length of C-D drawn through C perpendicularly to A-B.

"But from the nature of the voltaic excitation, the absolute magnitudes of the lines A-F and B-G are not determined, but merely the amount of the tension, or the length of the line G-H; consequently the mode of separation may be represented quite as well by any other line parallel to the former; e.g., by I-K, for which the tension still constantly retains the same value expressed by K-N, because the ordinates situated at present below A-B assume a relation opposed to their former one.

"Which of the infinitely numerous lines parallel to F-G would express the actual state of the ring, cannot be generally stated, but must in each case be separately determined from circumstances which occur. Moreover, it is easily conceived that as the position of the line sought is given, it would be completely determined for one single part of ring by the determination of any one of its points, or, in other words, by knowledge of the electric force.

"If, for instance, the ring lost all its electricity at the place, C, by abduction, (if the point, D, of ring, that is to say, were reduced to zero potential

by connecting it with a conducting body such as the earth, whose potential is assumed to be zero) the line L-M drawn through, C, parallel to F-G, would in this case express with perfect certainty the electrical state of the ring.

"It is to this variability in the separation of the electricity that the changeableness of the phenomnon peculiar to the voltaic circuit is to be attributed."

OHM then repeated his thought experiment with a circuit composed of any number of sections of varying size and material, and another circuit conductor formed of two parts of like cross-section but different materials, Fig. 7.3B. In each case he predicated a law that each section of conductor must receive from one side the same quantity of electricity that it gives off from the other side, i.e., that the current is of equal strength in all parts of the circuit. The variable must thus be the tension. Proceeding in this manner with his deductions, Ohm arrived at the following:

"In a galvanic circuit consisting of any indefinite number of prismatic parts, there takes place in regard to its electrical state at each place of excitation a sudden transition, from one part to the other, forming the tension there prevailing and within each part a gradual and uniform transition from the one extremity to the other; and the dips of the various transitions are inversely proportional to the products of the conductivities and sections of each part."

Ohm commented in one of his papers that he was not happy with the operation of the voltaic cells in his experiments. Due to the nullifying chemical action of polarization and because of local corrosion, the electromotive force of the early batteries declined rapidly under load, and they had a limited life. There were fluctuations in the output depending on the condition of the cells. J.C. Poggendorff, editor of *Annalen der Physik und Chemie,* and familiar with Ohm's work, suggested that he substitute a *thermoelectric generator* for his electric source.

THERMOELECTRICITY had been discovered by the Russian-born scientist Thomas J. Seebeck (1770-1831). Thermoelectricity operated on the principle that the junctions of dissimilar metals, such as bismuth and copper, when maintained at different temperatures, would produce a flow of current through a circuit. The generator gave a very low electromotive force, but it also had a low internal resistance, consequently delivered a large current. The electromagnetic effect from the current in the circuit was steady as long as the temperature differential was maintained on the junctions.

Although Ohm had accumulated many tests using voltaic cells, he found thermoelectricity preferable for his concluding investigations. Resistance of the thermoelectric circuit was measurable and stable, contrasted to the unpredictable internal resistance of the voltaic cells. Ohm found that the electromotive force of the generator was approximately proportional to the temperature difference of the thermoelectric junctions.

Ohm used the test arrangement of Fig.7.4. But, instead of calculating his readings with reference to the standard copper conductor, he used the figures shown by the torsion head directly for the dependent variable.

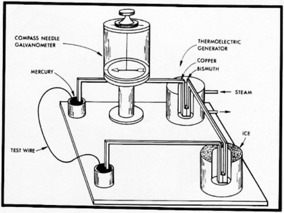
In January 1826 Ohm carried out one of his series of tests, using different metals and various lengths of wire for each. In one test he prepared eight samples of copper wire, of the same diameter, but lengths 2, 4, 6, 10, 18, 34, 66 and 130 inches. The current source was a thermoelectric generator, one junction being heated in a steam jacket and the other junction was in an ice pack. Ohm obtained the following results:

Length of copper conductor,inches	Restoring angle of torsion head in divisions
2	326¾
4	300¾
6	277¼
10	238¼
18	190¾
34	134½
66	83¼
130	48½

OHM'S CONCLUSION, from the above data and from previous tests of a similar nature, was that the

HOW OHM TESTED RESISTANCE . . .

Fig. 7.4 - Ohm's conclusions regarding the relations between electromagnetic force of the current, the potential, and length of the connecting test wire, were verified in a test arrangement such as this. Magnetic force of the current was measured by a Coulomb torsion balance galvanometer. Ohm found that resistance of a circuit could be determined by an equation involving the ratio of voltage to current.



results could be represented by an equation of the form:

$$X = \frac{a}{b + x}$$

where, X, the reading of the torsion head, is a measure of the electric current in a conductor of length, x. The quantities, a and b, were constants of the circuit whose values were to be determined by an additional series of experiments.

Ohm observed that, b, remained constant for all the series of tests, while, a, varied with temperature of the thermoelectric generator. He concluded that a, depended only on the electromotive force of the source, while, b, represented the resistance of the circuit.

Ohm gave a value of 20¼ for, b, and for the experiment in the Table on the previous page, a value of 7285 for, a. Thus, for example, for the conductor length of 18 inches, $X = 7285/20¼ + 18$ which works out to 190.72 compared to the measured value of 190¼. Other test lengths also agreed.

Ohm varied the experiments by using brass test wires and by changing the electromotive force of the thermoelectric generator by using ice in one junction and room temperature on the other.

The results of the formula held up.

OHM PUBLISHED in February and April 1826, two papers dealing with aspects of his theory of a galvanic circuit as derived from his extensive experiments. Together, the papers served to resolve the previously confused situation pertaining to open and closed circuits, and presented precisely for the first time the notions of the relations between the electric tension and the quantity of electricity which was delivered to the circuit.

Ohm's second paper contained the equation:

$$S = k\omega\left(\frac{a}{l}\right)$$

where, S, was the intensity of current produced by the tension, a, in a length of wire, l, cross-section, ω, and conductibility, k. By reducing the actual length of the wire and its cross-section and conductibility to an equivalent length of wire, L, chosen as a standard, Ohm simplified the equation to:

$$S = \frac{A}{L}$$

where, S, is the quantity of electricity passing through a given cross-section of the conductor in a unit time, A, is the difference of electric force between the extremities of the length of wire under test, and, L, is the "reduced length" of the


A
2164
B
0
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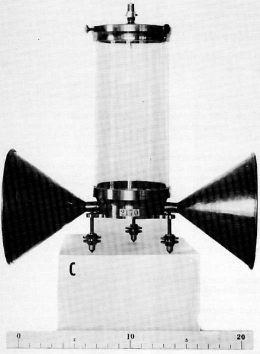


APPARATUS USED BY OHM . . . *now in the Deutsches Museum, Munich*

A - **BATTERY** - voltaic pile using copper and zinc plates

B - **GALVANOMETER** - using a compass needle mounted above a coil of wire

C - **THERMOMULTIPLIKATOR** - A thermogalvanometer containing two rectangular bars, probably one of bismuth and the other of antimony, one above the other at a distance sufficient to allow the lower magnet of an astatic needle to swing between them. Ends of the bars are soldered together, and the upper bar has a longitudinal saw-cut through which the lower suspended magnet can pass to its proper level.

circuit, which was equivalent to the sum of the resistances in the circuit.

The equation showed, as stated by Ohm . . . *that the force of the current is as the sum of all the tensions, and inversely as the entire length of the circuit.*

This became known as Ohm's Law, which in its usual equation form is:

$$I = \frac{V}{R}$$

When current, *I*, is produced in a conductor by an electromotive force, *V*, the ratio of the electromotive force to the current is independent of the strength of the current, and is called the resistance, *R*, of the conductor.

Some doubts had been raised with respect to the mathematical accuracy of Ohm's law, and as to the exactness of the proportionality between the electromotive force and the current in the same conductor. The subject was taken up by the British Association for the Advancement of Science, and in 1874 experiments were made by which the exactness of the law, as it relates to metal conductors, was tested by currents of every degree of intensity. The tests upheld Ohm's law, showing it was unambiguous and correct.

OHM'S WORK, theoretical and experimental, clarified the following principal points:

1 - Resistance is a unique property of a given conductor.

2 - The current flowing in a given circuit is directly proportional to the difference of potential at the two ends of the circuit.

3 - The current is directly proportional to the section of wire, and the current passing through the wire is everywhere the same.

4 - The current is directly proportional to the specific conductivity of the material of which the conductor is composed.

5 - The potential of a circuit connected to the source of electricity is highest at the positive pole of the source, and lowest at the negative pole.

The potential falls uniformly through the whole circuit, when the conductor is of uniform size, and otherwise falls uniformly through uniform resistance.

IN 1827, to complete his experimental work and to have access to better libraries, Ohm was given leave to go to Berlin. Here his great book: *The Galvanic Circuit Mathematically Worked Out* was published. It was a comprehensive volume, encompassing all of his earlier investigations, and was divided into three parts: "Introduction," "The Voltaic Circuit" and "Appendix."

To expound his theory of the galvanic circuit to the mathematically unsophisticated, Ohm, in the Introduction used an essentially geometric presentation. Some excerpts of his method and his conclusions have been given in previous pages.

Ohm' most important postulate, upon which his theory was based, was that the flow of electricity within a body depended on a particle to particle transfer proportional to the difference of electromotive force between them. Conductivity was thus a measure of the quantity of electricity transferred per unit of time across a unit of distance. The postulate had originated in an analogy with the theory of heat flow, and Ohm pointed out its similarity to the work of Fourier. From this postulate Ohm arrived at his general law that the current in a galvanic circuit is constant across all cross-sections, and is equal to the sum of all the electromotive forces divided by the total reduced length (resistance) of the circuit. This implied a change in electromotive force across each portion of the closed circuit.

The second part of Ohm's book was devoted to a mathematical presentation of the results he had deduced from his theory and experiments. The Appendix was a discussion of circuits in which the current was accompanied by a chemical change.

Ohm prefaced his book as follows:

"I HEREWITH present to the public a theory of galvanic electricity, as a special part of electrical science in general, and shall successively, as time, inclination, and the means permit, arrange more such portions together into a whole, if this first essay shall in some degree repay the sacrifice it has cost me.

"The circumstances in which I have hitherto been placed have not been adapted either to encourage me in the pursuit of novelties, or to enable me to become acquainted with works relating to the same department of literature throughout its whole extent. I have therefore chosen for my first attempt a portion in which I have the least to apprehend competition.

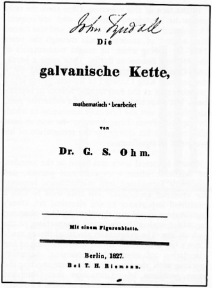
"May the well-disposed reader receive the performance with the same love for the objects that which with it is sent forth!"

Ohm's book appears not to have been fully appreciated by his contemporaries, and his law came into use only after considerable hesitation and delay.

Ohm was accused of offering in his book purely theoretical deductions without substantiating experimental proof. This accusation has been considered questionable, however, in view of the wide circulation of Ohm's previous papers reporting his experimental evidence, all available before the appearance of his book. Some described the hesitancy of immediate acceptance to the fact that many physicists of the time were lacking in the mathematical approach to science, whereas Ohm presented his theories primarily in that form. Ohm's conductibility equations seemed to some so simple as related to complex considerations, and to reality, that they were not acceptable. The obscurity of some of the definitions in the book, and the complication of presentation and logic of some of Ohm's writing may have been a hurdle to understanding and appreciation.

RECEPTION of Ohm's book by some critics was hostile. One of them called Ohm's theories a "web of naked fancies." Furthermore, the critic said, "he who looks upon the world from this book as the result of an incurable delusion, whose sole effort is to detract from the dignity of nature." A doctrinaire school official who was opposed to the mathematical school of thought, and to Ohm's book, stated his objections to the Minister of Education at Berlin. Accepting this report uncritically, the Minister pronounced that "a professor who preached such heresies was unworthy to teach science!"

The cause of this harassment and Ohm's failure to get his aspired university post has been ascribed to ideological and political situations. The Berlin


John Tyndall

Die

galvanische Kette,

mathematisch · bearbeitet

von

Dr. G. S. Ohm.

Mit einem Figurenblatte.

Berlin, 1827.
Bei T. H. Riemann.

Fig. 7.6 - TITLE PAGE of Georg S. Ohm's great work *The Galvanic Circuit Mathematically Investigated,* in which appeared the fully developed presentation of his theory on the relations of the electric circuit. This title page is from a copy of Ohm's book in the possession of the Burndy Library. The signature at the top is that of John Tyndall, the English scientist and lecturer, who succeeded Michael Faraday as Director of the Royal Institution, London.

academic establishment was in the grip of the Hegelian philosophy which was sweeping Germany at the time. Hegel's philosophy held that Nature is a realm of law and order, open to the mind without the aid of matter - an attitude against the need for experiment, and somewhat anti-science. On the political side, Ohm's brother Martin, with whom Ohm lived in Berlin, had clashed with Berlin officialdom because of his criticism of the educational system, and was considered a dangerous revolutionary, and this situation contributed to the rejection of Ohm's work.

In the face of this rejection, Ohm took the only course he considered consistent with self-respect. He resigned his position at Cologne, and was forced into a kind of academic exile through the years 1827-31, during which he taught mathematics at the Military School in Berlin. Then came a break, and Ohm's discouragement was assuaged by a decree from King Ludwig I of Bavaria, giving him a professorship at the Polytechnic School of Nuremberg. But Ohm had ambitions for a university post, and this was not the first-rank institution to which he aspired. From here, however, he was at least able to press his claims for the recognition of his work and its significance.

Ohm's electrical work was based on the soundest of scientific effort - experimental pursuit, and discovery formulated into mathematical language for universal application. His laws were to have a profound importance to the electrical art. Ohm's publications could not therefore be long obscured by wilful neglect, bureaucratic obstruction, or the lack of use. The progress in electrical theory made Ohm's law a necessity in the understanding of and calculation of electrical phenomena. Scientists working with electrical circuitry were meeting the same problems of relationships that Ohm had solved. They gradually learned of Ohm's research and appreciated the elegance and utility of his fundamental law.

JOSEPH HENRY, in America, Wheatstone in England and Lenz in Russia, among other active investigators in electricity, admired Ohm's work and began to give it publicity. Then, the younger physicists, dealing with and writing on electricity, subjected Ohm's law to test and confirmation, and began to include it in textbooks. However, it was not until the 1840s that the scientific world generally became aware of the great implications of Ohm's writings.

The crowning accolade came in 1841 when the Royal Society of London awarded him the Copely Medal, their highest and most coveted honor, in recognition of his law.

In 1849 Ohm received the first mark of substantial recognition and merit from his home country. At the end of 1849 Ohm was appointed by the Emperor Maxmillian II, as Professor of Physics to the University of Munich, and the Akademie of Science selected him Conservator of Mathematical Physics. These positions fulfilled one of the great ambitions of Ohm's life. His name was now being honored in all scientific circles, and Ohm was inspired to renew and broaden his scholarly and experimental efforts. His later work was mostly in fields of acoustics and crystallography, and he was an early investigator in molecular theory.

In addition to research, Ohm was an innovative and effective teacher. His brother, Martin, who taught at the University of Berlin, was among the first to stress the importance of a training in mathematics as prerequisite for the understanding of science. This flew in the face of tradition, however, particularly in the military where promotion had been by the privilege of birth rather than from superiority achieved by an imposed scientific training. Hence, adoption of mathematics in the curriculum lagged in Germany. Holding his brother's views, Ohm insisted that mathematics be coordinated with physics as the best basis for achieving practical scientific knowledge. He personally prepared mathematical material for his students, and pioneered the "example" method of demonstrating the use of mathematics in physics.

Ohm's last years were spent in the realization of his dreams finally come true - a first-rank university post, an honored place in science, the respect of colleagues, and the admiration of his students. He carried on his University duties until his death in 1854 at the age of 65. Ohm never married.

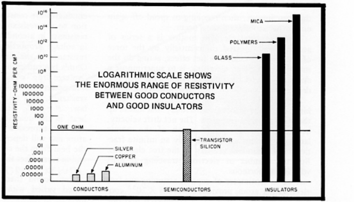
Ohm's scientific writings and research notes were collected and published in Leipzig in 1892, under the editorship of Dr. Eugene Lommel, Professor of Physics at the University of Munich. The book of 855 pages covers the results of Ohm's efforts extending for a period of over thirty years.

RESISTANCE was the first electrical property to come under concerted scientific attention for standardizing. The British Association Committee on Standards of Electrical Resistance, appointed in 1861, adopted a standard unit of resistance in 1862. It was first named the "Ohmad," and this was finally abbreviated to "Ohm." Meeting in Paris in 1881, the International Electrical Congress paid the ultimate homage to Ohm by confirming his name for the practical unit of electrical resistance.Thus was initiated the practice of naming units after the founders of the science, a practice which has continued to this day.

RANGE OF RESISTIVITY

Fig. 7.7- Resistivity of various conductors and insulators is shown on a logarithmic scale. This reveals the enormous spread in resistivity values, about 10 to the 25th power, between the best conductors and best insulators. This characteristic is due to the nature of the electron bonding in various materials, to provide the availability or absence of free electrons for conduction.

The enormous range of resistivity is a fact of nature that makes possible all of our present electrical technology.



OHM'S WORK was a link bridging the time-gap existing between the static electricity of previous ages, and the new era of voltaic current. Whereas static electricity resided on the surface of the conductor, Ohm saw the circuital current as electricity in motion, penetrating the interior and utilizing the volume of the metal wires. For this to occur, Ohm visualized an elemental, particulate structure of matter. The current in the wire, he conjectured, was a transfer of the electrical fluid from particle to particle. The transfer was accompanied by a uniform drop in potential, particle by particle, in forcing the current against resistance in the conductor. Nothing was known of the nature of the electrical "particles" in Ohm's time. But later discoveries would reveal their structure.

Investigations in the 19th and early 20th centuries revealed the atomic elements of matter, and the fact that the atoms had a composition of electric charges. The protons of the atomic nucleus provided positive charges, and the atomic electrons provided negative charges. Electrons were the electric charge carriers in solids and gases. Ions, which resulted when atoms or groups of atoms gained or lost electrons, provided either positive or negative electric charge carriers in solutions and plasmas. The flow of these charge carriers constituted the electric current.

The metals are the best conductors we know of, and Ohm was the first to determine the order of their conductivity. To account for the high conductivity of metals, the "free electron" theory was developed early in the 20th century. This theory was based on a view of the electrons in discrete motion within the crystalline structure of the metal conductor. In the metallic atomic bonding, certain of the outer electrons, about one per atom, become loose in the sense of no longer being localized in an individual atom, but belonging to the crystal as a whole. Freedom of these electrons leaves a residual lattice of positive ions in the metal, within which the free electrons can wander.

The atomic structure is in a constant state of vibration, the intensity of which is determined by the temperature. The atoms impart some of this vibrational energy to the free electrons, putting them into a mazy motion. The electrons randomly collide with the ionic lattice and recoil in a manner similar to the molecular collisions in a gas. The motion of the free electrons provides the mechanism for the conduction of electricity.

When an electric potential is applied to the conductor, a force will be superimposed on the random motion of the free electrons, causing them to accelerate directionally. By convention the direction is opposite to that of the electric field. The acceleration acts for a very brief interval until the electrons collide with neighboring atoms, giving

them an impact, then recoiling to speed off again until other atomic collisions occur.

Thus the total electron motion is a series of accelerations directed preferentially by the force of the electric field. The net effect, acting on the totality of the free electrons, is to superimpose a drift velocity on their normal random motion. The drift velocity constitutes the electric current.

The amount of current will depend on a combination of the velocity and density that makes up the charge carrier transport. The net drift velocity, because of the scattering action of the atomic lattice, is exceedingly small, only an infinite fraction of the random velocity of the free electrons. But the number of electrons traveling at drift velocity is enormous.

A cubic centimeter of copper, assuming one free electron per atom, provides about 8.5×10^{22} conduction electrons. When it is considered that one ampere consists of the flow of 6.26×10^{18} electrons per second, the availability of a sufficient number of charge carriers for very large currents is apparent.

NET DRIFT VELOCITY varies with the strength of the electric field. For most metals the drift velocity, and hence the current, is directly proportional to the voltage that is applied. The proportionality factor between the current and the voltage can be expressed as the *conductance, G.*

The current will then be a product of the voltage and the conductance, or, $I = GV$. Since resistance is the reciprocal of conductance, that is, $R = 1/G$, there is an alternate equation for the current, using resistance, that is, $I = V/R$. Thus the drift velocity theory operates in conformity with Ohm's law.

The ratio of the voltage to the current, where Ohm's law applies, is constant, and can be plotted as a straight line, or linear relationship. Slope of the line is determined by the resistance, expressed by Ohm's law, or, $R = V/I$. This straight-line relationship has been shown to be valid up to the highest range of practical current density for most metal conductors. Hence, resistance is a definite property of the metal.

Imparting a drift velocity to the free electrons in a conductor results in much more vigorous collision impacts with the atoms of the conductor, thus doing work on them, and this increases their thermal vibration. The voltage and energy of the conductor are consumed in this process in proportion to the resistance of the conductor. Thus the resistance in a conductor manifests itself by a drop in voltage proportional to the current and to the resistance in the circuit. This is expressed by the Ohm's law equation: $V = IR$, commonly called the "voltage drop" equation.

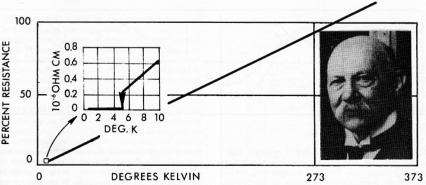
A power loss is also involved in overcoming the resistance, and this loss is expressed by Joule's law: $P = I^2R$. The power loss is converted into heat, in the quantity equivalent to joule-seconds, or, I^2Rt, expressed in watts. The resulting temperature rise will depend on the rate of dissipation of the heat from the conductor. Any temperature rise will in turn affect the resistance of the conductor.

Ohm found that the resistance of metals he tested varied with temperature. There was an increase in resistance with increase in temperature, and vice versa. Thus. resistance was not only a characteristic of the individual metal, but was also dependent on the temperature. A resistance value must therefore include the temperature at which it holds. Much research has gone into development of metal alloys for minimum resistance variation with variation of temperature.

SUPERCONDUCTORS - Ohm could never have imagined that the resistance of a conductor could disappear completely. But his discovery that the resistance was affected by temperature was a first step that culminated, nearly a century later, in the achievement of zero resistance.

H. Kamerlingh Onnes (1850-1926), a Dutch physicist, succeeded, in 1908, in Leyden, Holland, in liquefying helium, and thereby had attained a temperature of 4.2 degrees Kelvin. Later, by boiling helium regeneratively, he was able to get even closer to zero degrees. From the known facts of the drop in resistance with a drop in temperature, it was apparent to Onnes that if temperature could be lowered to absolute zero, resistance would tend to vanish. With the means of achieving a temperature near to zero, Onnes was now able to pursue an investigation into the possibility of zero resistance.

He first experimented with platinum, but was unable to get the resistance below a certain critical value. He blamed this on supposed impurities in the metal. Assuming that it could be had in a much purer state, he next tried mercury, and found in



1911, that at a temperature of 4.2 degrees Kelvin the resistance of the mercury fell sharply to zero. Fortunately, the transition to zero resistance had occurred within the limits of low temperature refrigeration available at the time. Onnes called this extraordinary electrical state of a conductor - *superconductivity*.

Onnes later found that lead reached the zero-resistance state at 7.2 degrees Kelvin, and tin at 3.7 degrees. Other metals entered the state of superconductivity at their certain so-called *critical* temperatures. Onnes saw at once that conductors of zero resistance could carry large current without the usual heat dissipation. This would be accompanied by magnetic fields much larger than was possible with conductors at usual temperatures. But he found that at even moderate magnetic field strengths, the superconductivity would suddenly be quenched, and the normal resistance would be restored.

The possibilities of improving performance of electromagnetic apparatus by use of superconductors did not emerge until 50 years after Onnes had made his original investigations. A break-through came after World War II with the discovery that conductors using alloys of niobium, vanadium and other "transition" elements, could carry current densities of thousands of amperes, and very large magnetic fields, without quenching. The remarkable properties of these alloys stimulated research for new types of superconductors which were

ONNES DISCOVERS SUPERCONDUCTIVITY . . .

Fig. 7.8 - The sudden fall to zero of the electrical resistance of some metals at very low temperature was first observed by the Dutch physicist, H. Kamerlingh Onnes (above) in Leyden, Holland, in 1911. The first metal to go into the zero-resistance state was mercury, at 4.2 degrees Kelvin. Onnes called this electrical phenomenon *superconductivity*.

operative at higher critical temperatures, and for materials that could satisfactorily be drawn into wires.

Superconducting alloy materials with critical temperatures up to 25 degrees Kelvin have been developed. Metal-clad alloy wires can now be wound into electromagnets to operate with possible current densities up to 10^6 amperes, and yielding fields up to 50 teslas (50×10^4 gauss).

Now, with fabrication of transition-metal alloys into wires, and with developments in cryogenics, the field of low-temperature refrigeration, wide areas of application for high-intensity magnetic fields have opened. Present-day technology is built around the copper-wound, iron-core magnetic solenoid, which saturates at about 2 teslas, or, 20,000 gauss, and this constitutes the upper limit of conventional magnetic fields. Superconducting magnets promise to multiply this many times.

Superconductivity, with its ability to produce intense, large-volume fields, is now being pioneered for electric power generation and transmission, and

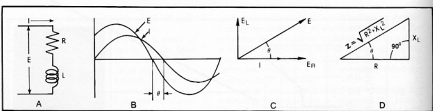


Fig. 7.9 - OHM'S LAW for an a-c circuit, Fig. A, containing ohmic resistance, R, and inductance, L. Inertia effect of the magnetic field, L, causes the current to lag the voltage by and angle, θ, Fig. B. Thus the voltage, E, and the current, I, are related geometrically, Fig. C. The impedance, Z, of the circuit, Fig. D, is the vectorial addition of the resistance, R. and the inductive reactance, X_L, which are at a right-angle relationship to each other.

for application to nuclear fusion systems, high-energy particle accelerators, and magnetohydrodynamic apparatus. There is a continuing search for better materials and methods of fabrication that will yield higher intensity magnetic fields.

CONVERTING OHM'S LAW for Alternating Currents - Ohm's law assumes a steady electrical state, and applies very simply to direct-current circuits, that is $I = V/R$. With the introduction of alternating-current systems, where the voltage and current change direction rapidly and periodically, this simple relationship no longer holds. Ohm's law was then thought to be on forbidden ground. However, in the late 19th century, the needs of a-c calculation brought forth, by mathematical manipulation, a new variety of Ohm's law that was applicable to alternating-current circuits.

In alternating currents, Ohm's law assumes the new form: $I = V/Z$, where, Z, is the "apparent" resistance, or *impedance,* and is no longer constant, but depends on the frequency of the circuit.

The impedance has two components: *resistance, R,* and the *reactances, X.* The principal sources of the reactances are electromagnetism and electrical capacity of the a-c circuit.

The periodic alternation of voltage and current in a-c circuits introduces two frequency-dependent effects. The first effect operates on the *magnetic inductance of the circuit, L,* because of the periodically changing magnetic fields, to produce an *inductive reactance,* X_L. The second effect operates on the *electrical capacitance of the circuit, C,* because of the periodically changing electric fields, to produce a *capacitative reactance,* X_C.

The voltage and current consumed in heat losses, due to ohmic resistance, *R,* are in phase with each other, independent of frequency, and related to each other by Ohm's law. The current of the magnetic fields, because of magnetic inertia, *lags* 90 degrees behind its voltage, and is related to it by the inductive reactance, X_L. The current of the electric fields, because of electric elastance, *leads* its voltage by 90 degrees, and is related to it by the capacitative reactance, X_C.

Because of the quadrature relationship of these voltages and currents, the magnetic and electric fields represent merely a surging of energy back and forth in the circuit, and are called "wattless."

The reactances, *X,* can be expressed for any frequency, *f,* and for any value of inductance, *L,* or capacitance, *C,* by Ohm's "laws":

$$\text{Ohms Inductive Reactance} = 2\pi f L = X_L$$

$$\text{Ohms Capacitative Reactance} = \frac{1}{2\pi f C} = X_C$$

All a-c circuits will be some combination of the *resistance, R,* and the difference of the *reactances,* X_L and X_C in vectorial addition, giving the total:

$$\text{Ohms Impedance} = \sqrt{R^2 + (X_L - X_C)^2} = Z$$

OHM'S LAW is thus re-established for a-c circuits by replacing resistance, *R,* by the impedance, *Z.*

THE VARIATIONS in the manipulations of Ohm's law, and the uncountable ramifications of resistance in all manner of devices, are the essential pillars supporting the electrical technology of today. Resistance, its kind and control, wanted or unwanted, enters into the design, fabrication and efficiency of every electrical element from the microscopic to the gargantuan.

ALTERNATING - CURRENT MOTORS are an example of the use of resistance to achieve desired performance. Resistance is an essential element in the production of torque in induction and synchronous motors. Control of this resistance provides the fundamental method of designing the shape of the torque curve from standstill to full motor speed. Torque of the induction motor is at its maximum point when the rotor resistance, and the rotor inductive reactance, are equal. The amount of resistance with relation to the reactance affords the means of varying the torque curve to meet the starting and running requirements of the motor.

The Design D starting torque curve for an induction motor, shown in Fig. 7.10, develops maximum torque at standstill, where the high-resistance cage winding matches the inductive reactance at zero speed. The Design B motor, on the other hand, develops maximum torque near full speed, where the low-resistance rotor cage winding matches its inductive reactance.

The wound-rotor induction motor provides a means of matching the resistance to the reactance at all speeds, by use of an external resistor in the rotor circuit. Successive shorting out of steps of the resistor supplies a series of high starting torque curves as shown in Fig. 7.11.

The synchronous motor starts as an induction motor by use of cage bars in the tips of the rotor poles. With bars of appropriate resistance, and with bar placement in the poles for proper reactance, a wide variety of torque curves can be obtained to meet a wide range of drive requirements.

The double-cage rotor construction shown in Fig. 7.12, provides a combination of starting and running torques. The upper, high-resistance cage delivers a high breakaway torque. The deep, low-resistance cage matches the reactance at full speed, providing high torque during the starting period.

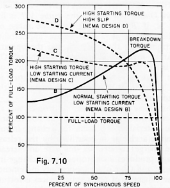


Fig. 7.10

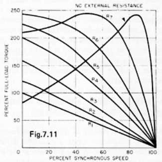


Fig.7.11

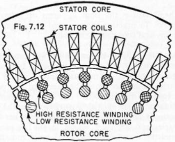


Fig. 7.12

OHM'S LAW IN OPERATION - A conductor obeys Ohm's law where the curve V/I is linear, that is, if R is constant over the range of its application. It is a law whose applicability is determined by the material, and the operational situation to which it is applied. Although Ohm's law is an experimental relationship, it holds over a wide range of conditions. With temperature taken into account, it is obeyed, in metals, within a broad spread of current densities.

Ohm knew nothing about electronics, nor about devices where resistance might be non-linear. For some materials it is possible for a change in voltage to cause a change in resistivity by the release of more charge carriers. In this case an increase in voltage produces a disproportionate change in the current, and Ohm's law applies only incrementally.

The existence of non-ohmic devices is fortunate. Otherwise, much of electronic technology would not exist, and modern life would be vastly different. The vacuum tube and semiconductor diodes are typical non-ohmic devices: the current vs voltage is non-linear. In the diode, the resistance characteristic is asymmetrical, passing the current in one direction and blocking it in the other. Some devices have a negative resistance in part of their operation, and in these cases Ohm's law needs special interpretation.

WHAT IS AN OHM? The ohm is defined in the International System of Units (SI) as:

The ohm is the electrical resistance between two points of a conductor when a constant difference of potential of 1 volt, applied between the points, produces a current of 1 ampere, the conductor not being the source os any electromotive force.

The SI defines the ohm in terms of volts and amperes. In practice there is need for a reproducible physical standard of the ohm.

In 1851, Wilhelm Weber (1804-1891), an experimental scientist in Germany, proposed an electromagnetic system of measurement in which the electrical resistance would be expressed as a velocity, equal to the distance of one earth quadrant, or 10^9 cm/sec. The British Association for the Advancement of Science, responding to the needs of the telegraph engineers, set up, in 1861, a pioneer committee to establish electrical units and standards. They adopted the system proposed by Weber. For the standard of resistance, the BA committee prepared, in 1864, a metal-alloy, wire-wound ohm as a standard to represent Weber's 10^9 electromagnetic velocity units. The BA resistance standards of this type were in use for about twenty years.

In 1860, to resolve the differences in the various resistance measurement standards existing in Europe at the time, and to provide a reproducible ohm, Werner Siemens, the German scientist, proposed independently a standard for the ohm. It was a column of mercury of one square millimeter section, one meter length, at the temperature of melting ice. This found wide acceptance as the standard ohm.

The column length was later increased to 106 cm for greater accuracy. In 1884 the "International Ohm" was standardized as the resistance, at zero degrees C, of a column of mercury 106.300 cm in length, of constant section, and weighing 14.4521 grams. This ohm was the standard for many years until development of newer precision methods of establishing the standard for the absolute ohm.

Since 1948, the legal standard absolute ohm has been defined in terms of the reactance to an alternating current of a calculated standard inductor or capacitor. If an inductor of known impedance: $z = 2\pi fL$, or a capacitor of a known impedance: $z = 1/(2\pi fC)$, is placed, at a known frequency, in one arm of an alternating-current bridge, it can be balanced against a resistor in the other arm to establish precisely the value of the resistor in ohms.

A computable capacitor for the alternating-current bridge method of ohm determination, is shown in Fig. 7.13, being assembled at the National Bureau of Standards. It uses a new form of a segmented capacitor tube, enabling the precise measurement of the absolute ohm.

PRIMARY STANDARDS for resistance measurement are made in various forms, one of which is shown in Fig. 7.14. This type of one-ohm standard was developed at the National Bureau of Standards by Dr. J.L. Thomas for use as a reference standard in laboratories requiring extremely high precision. The resistance element uses a wire alloy of copper, manganese and nickel having a low temperature coefficient of resistance. The wire is wound bifilar, hermetically sealed, and mounted in the outer case. In use, the standard is placed in an oil bath, maintained at a constant temperature, usually 25 °C.

Fig. 7.13 - COMPUTABLE CAPACITANCE STANDARD for absolute determination of ohm by a-c bridge method. Courtesy National Bureau of Standards, Washington, D.C.

Fig. 7.14 - PRIMARY RESISTANCE STANDARD of the wire-wound, hermetically sealed Thomas type, provides precise one ohm resistance. Courtesy Leeds & Northrup Co.

THE ONE HUNDREDTH ANNIVERSARY of Ohm's birth was commemorated, in 1889, by a group of scientists, meeting at the Royal Bavarian Academy of Sciences, at Munich. The following passage from Professor E. von Lommel's address at the meeting, as quoted in *Makers of Science,* by Ivor Hart, Oxford Press, pays tribute to Ohm:

"The deeds of a man of science are his scientific investigations. Truth once discovered does not remain shut up in the study or the laboratory. When the moment arrives, it bursts its narrow bonds and joins the quick pulse of life. That which has been discovered in solitude, in an unselfish struggle for knowledge, in pure love of science, is often fated to be the mighty lever to advance the culture of our race. When, nearly a hundred years ago, Galvani saw the frog's leg twitch under the influence of two metals touching, who could have suspected that the force of Nature which caused those twitchings would transfer the thought of man to far distant lands, with lightning speed, under the water of the ocean and would even render audible at a distance the sound of the spoken word?"

That this force of Nature - after man by ceaseless investigations had learned vastly to increase its strength - would illuminate our nights like the sun. This enormous development of electrotechnology could only be accomplished upon the firm foundation of Ohm's law. Ohm, by wresting from Nature her long-concealed secret, has placed the sceptre of this dominion in the hands of the present."

AND NOW, more than a century and a half after its formulation, Ohm's law stands, unchanged and unambiguous. as perhaps the most basic and the most widely used of all the laws in the electric science.